The road ahead for wireless technology: *Dreams and Challenges*

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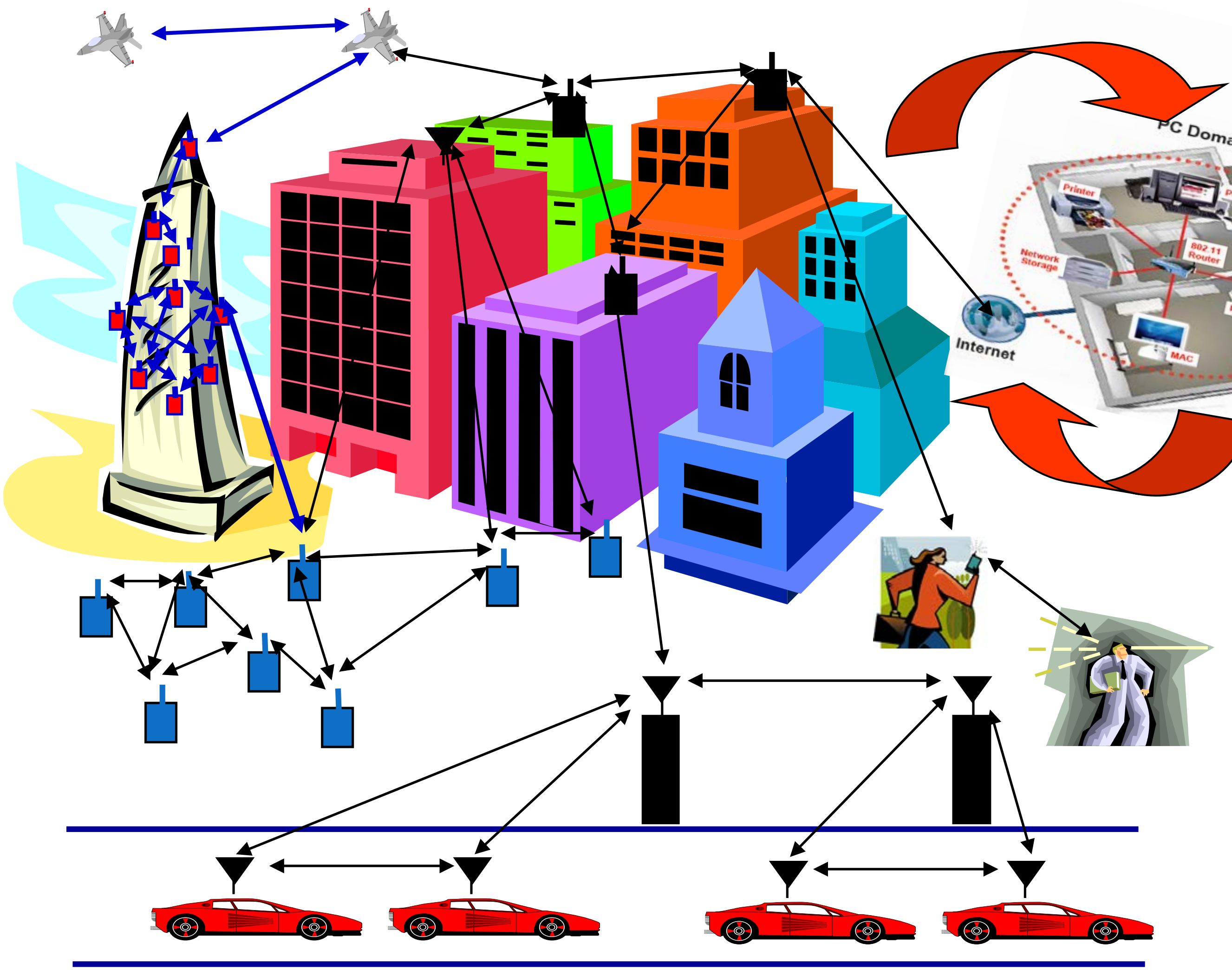
Future Wireless Networks

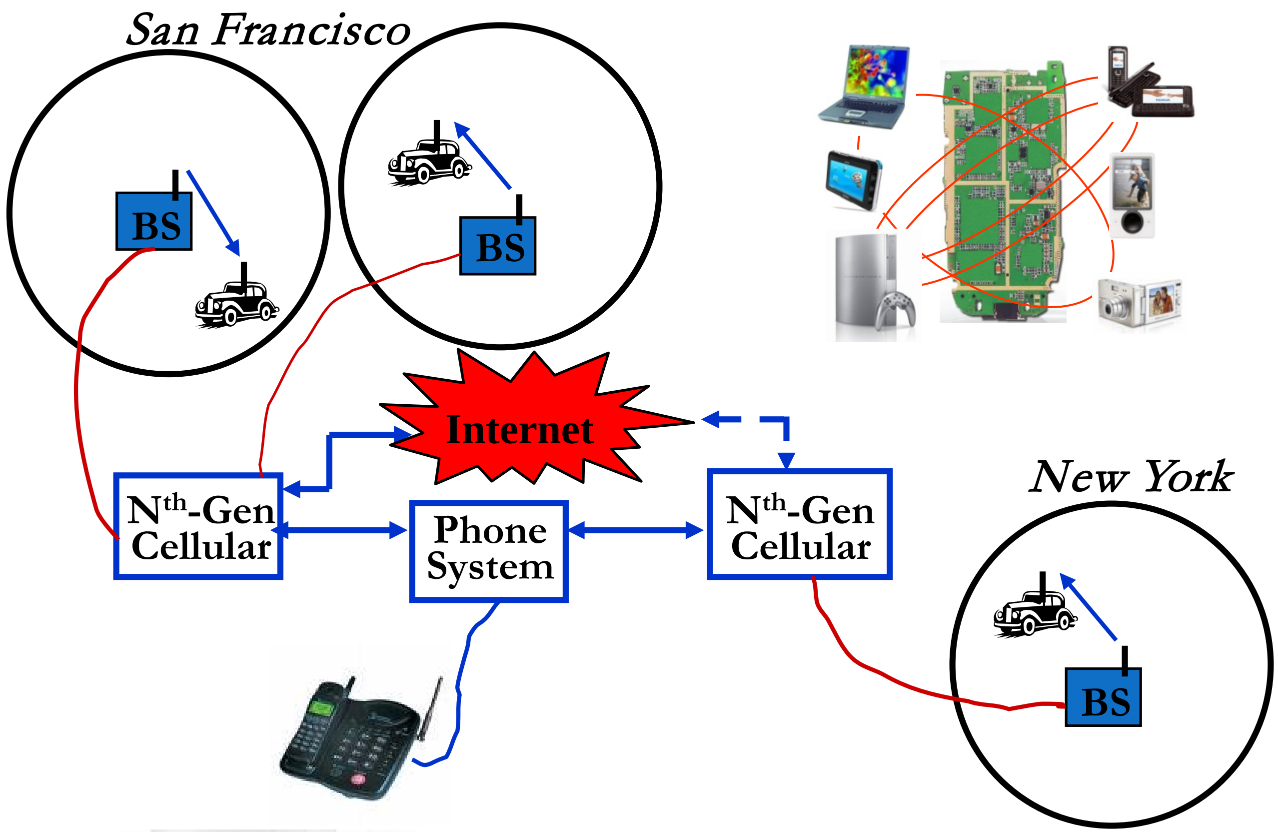
Ubiquitous Communication Among People and Devices



Next-generation Cellular
Wireless Internet Access
Wireless Multimedia
Sensor Networks
Smart Homes/Spaces
Automated Highways
Smart Grid
Body-Area Networks
All this and more …

Future Cell Phones

Burden for this performance is on the backbone network



Much better performance and reliability than today

- Gbps rates, low latency, 99% coverage indoors and out

Future Wifi:

Performance burden also on the (mesh) network

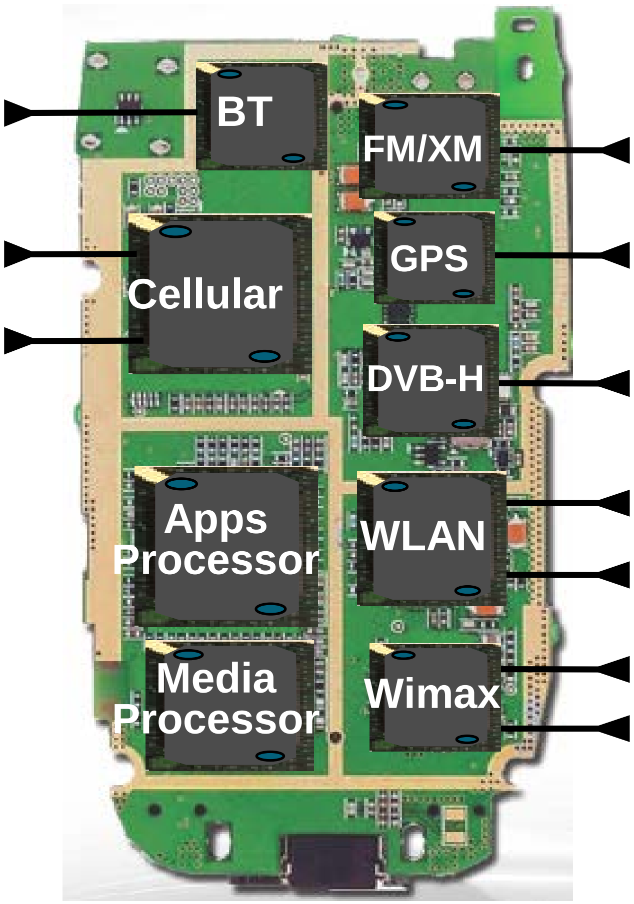
802.11n++

- Streaming video
- Gbps data rates
- High reliability
- Coverage in *every* room

Wireless HDTV
and Gaming

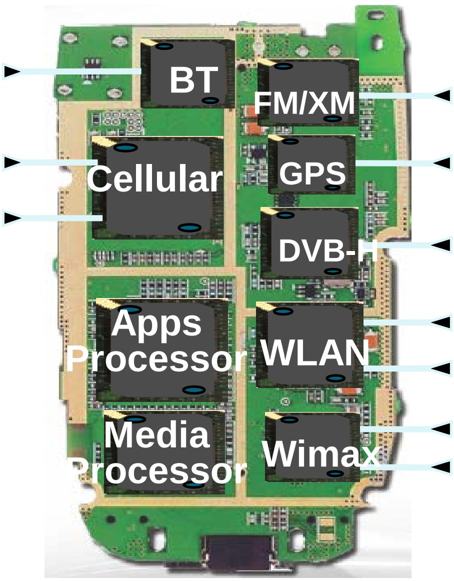
Device Challenges

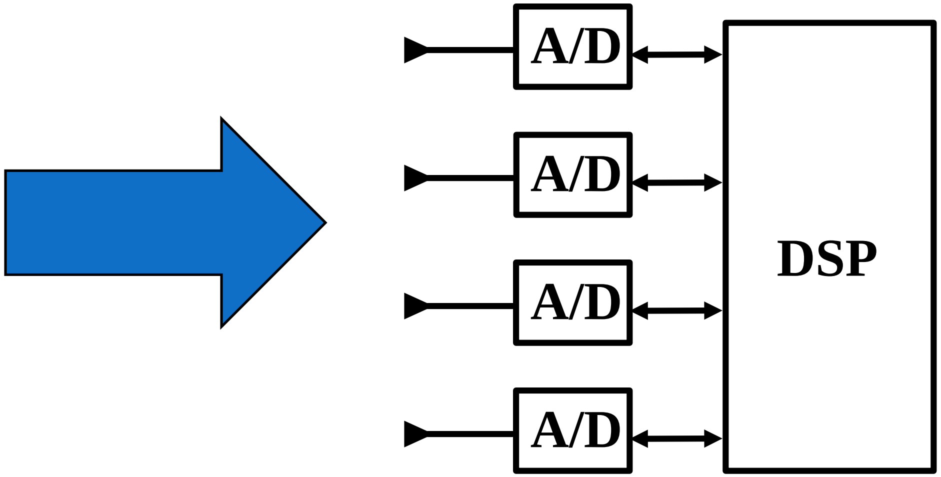
- Size and Cost
- Power and Heat
- Multiband Antennas
- Multiradio Coexistance
- Integration



Software-Defined (SD) Radio:

Is this the solution to the device challenges?





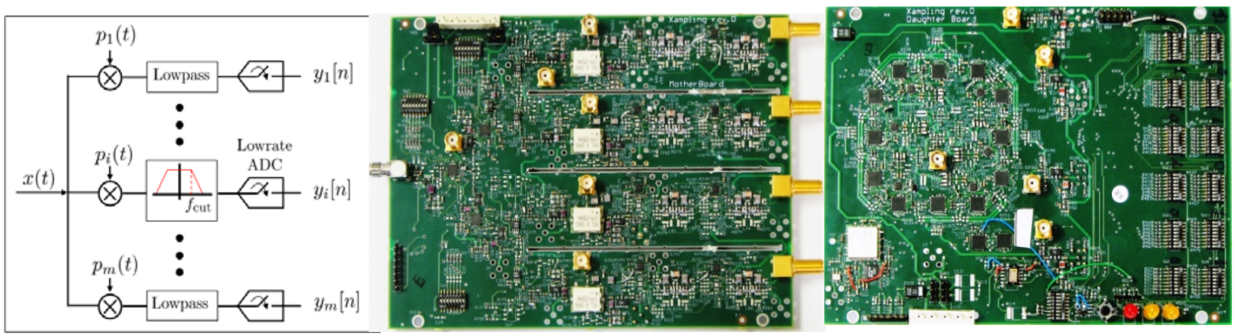
- Wideband antennas and A/Ds span BW of desired signals
- DSP programmed to process desired signal: no specialized HW

Today, this is not cost, size, or power efficient

Compressed sensing may be a solution for sparse signals

Compressed Sensing

- Basic premise is that signals with some sparse structure can be sampled below their Nyquist rate

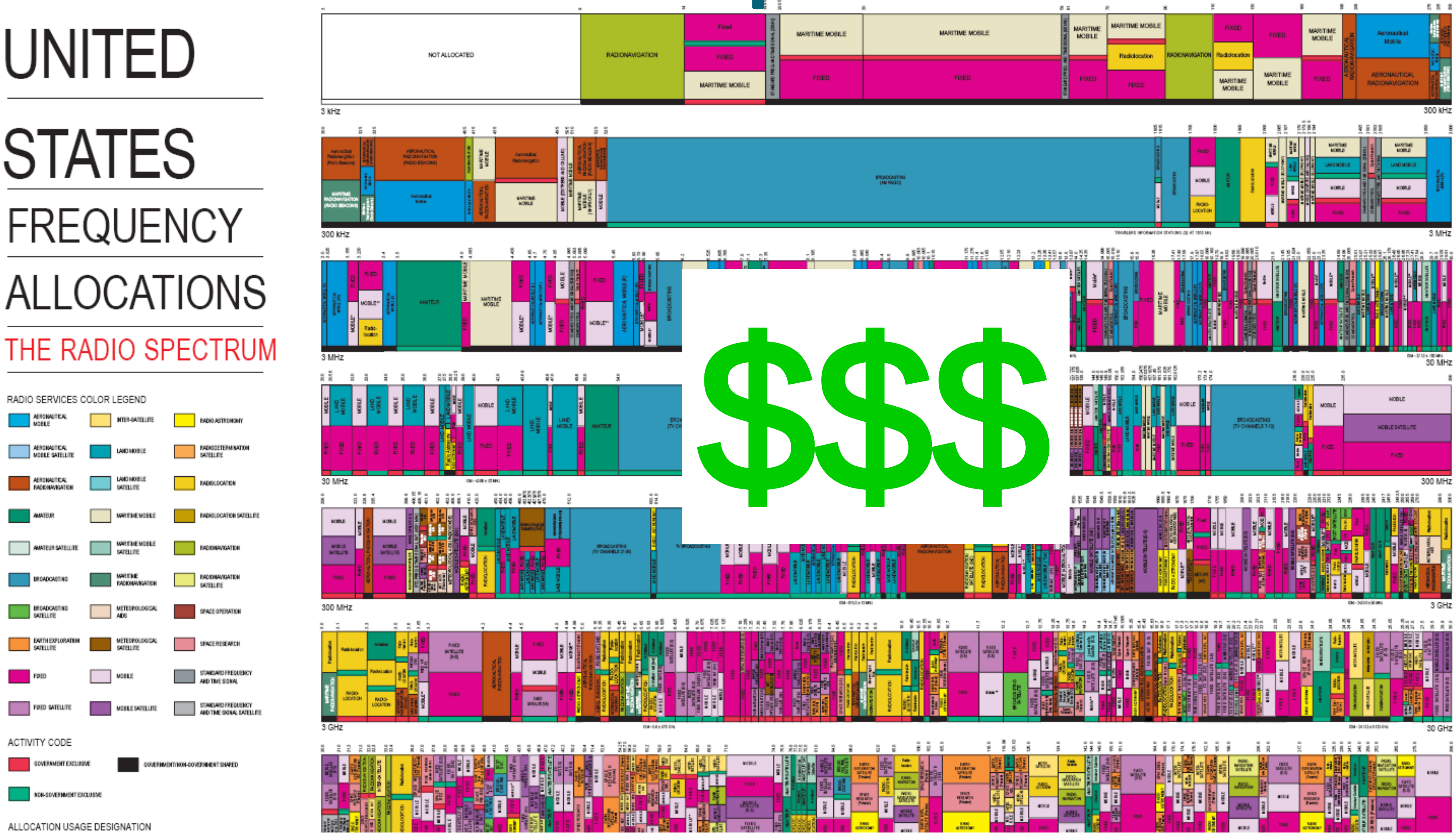


- Signal can be perfectly reconstructed from these samples by exploiting signal sparsity

- This significantly reduces the burden on the front-end A/D converter, as well as the DSP and storage

- Might be key enabler for SD and low-energy radios
  - Only for incoming signals “sparse” in time, freq., space, etc.

Scarce Wireless Spectrum

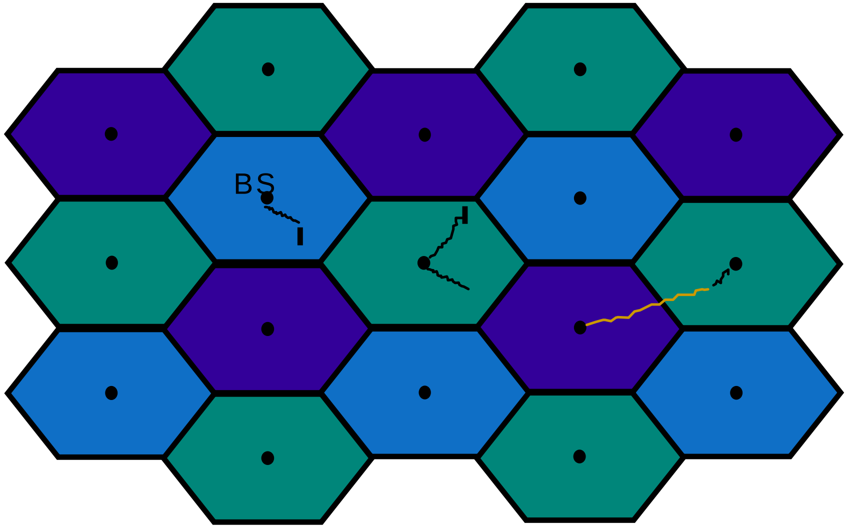


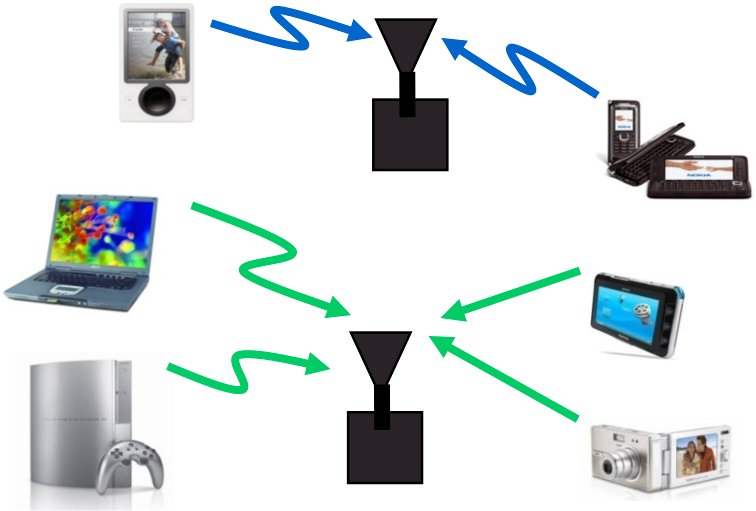
Hence regulated, and expensive

Spectral Reuse

Due to its scarcity, spectrum is *reused*

In licensed bands **and unlicensed bands**





Cellular, Wimax **Wifi, BT, UWB,…**

Reuse introduces interference

Interference: *Friend or Foe?*

- If treated as noise: Foe

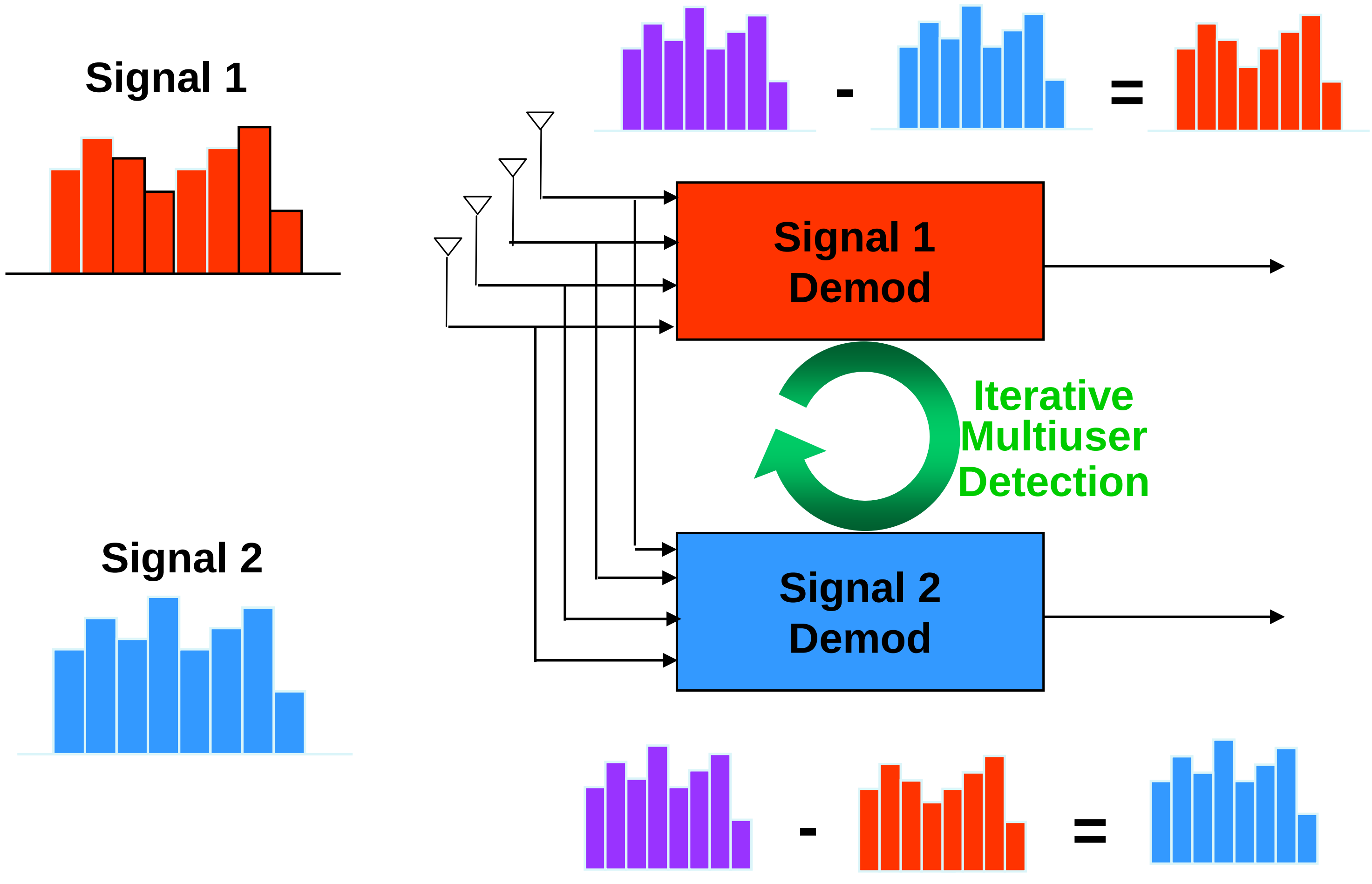
$$SNR = \frac{P}{N + I}$$

Increases BER, reduces capacity

- If decodable: Neither friend nor foe

Multiuser detection can completely remove interference

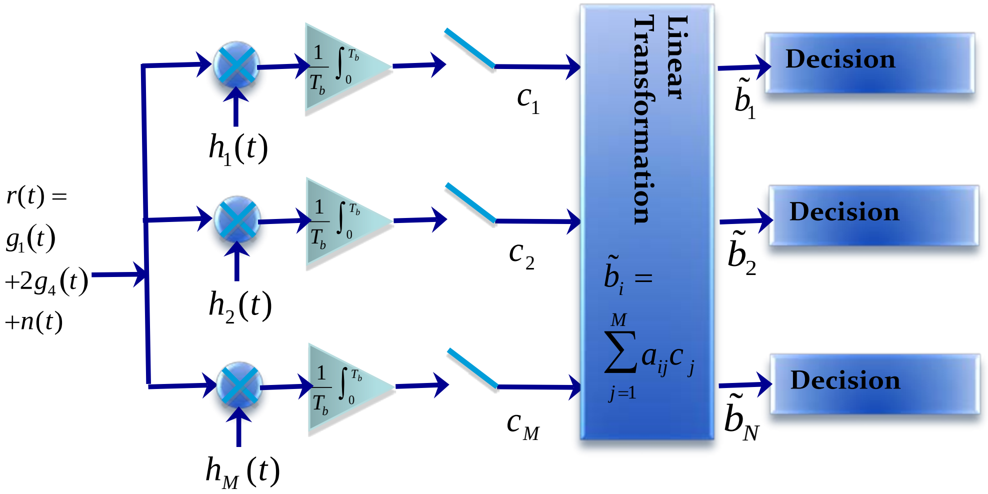
Ideal Multiuser Detection



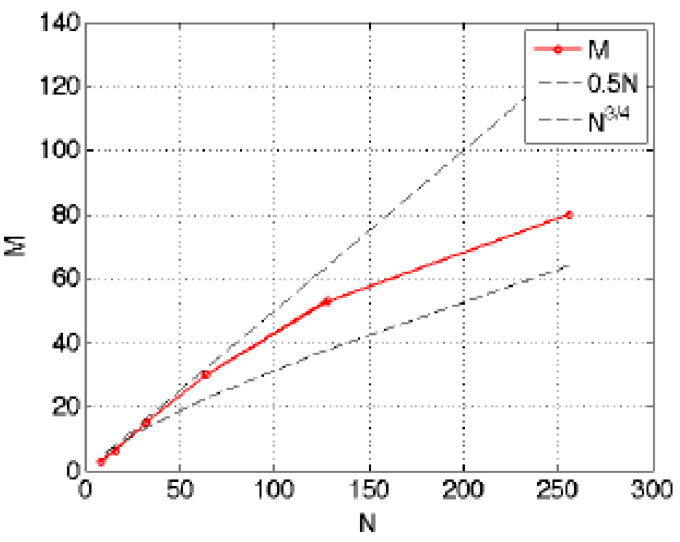
Why Not Ubiquitous Today? Power and A/D Precision

Reduced-Dimension MUD

- Exploits that number of active users G is random and much smaller than total users (ala compressed sensing)
- Using compressed sensing ideas, can correlate with M~log(G) waveforms
- Reduced complexity, size, and power consumption



10% Performance Degradation



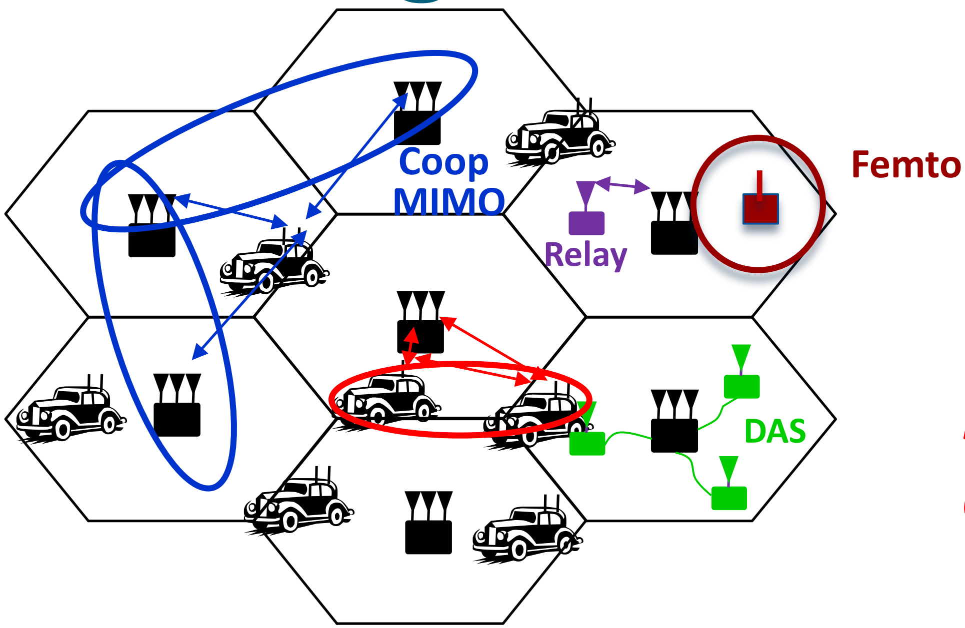
Interference: *Friend or Foe?*

If exploited via cooperation and cognition

Friend

Especially in a network setting

Rethinking "Cells" in Cellular



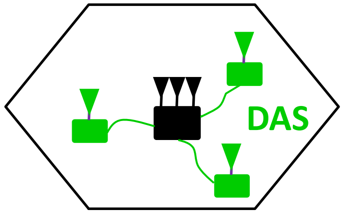
How should cellular systems be designed?

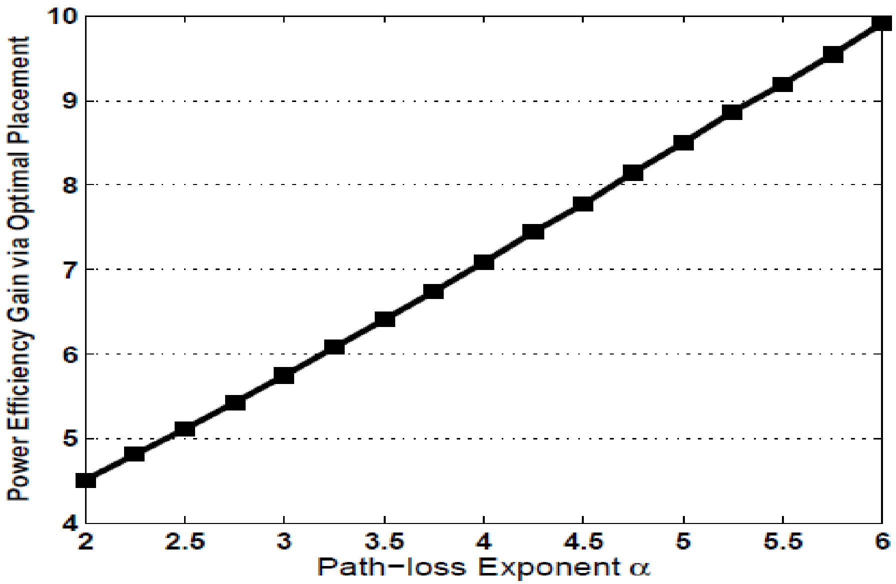
Will gains in practice be big or incremental; in capacity or coverage?

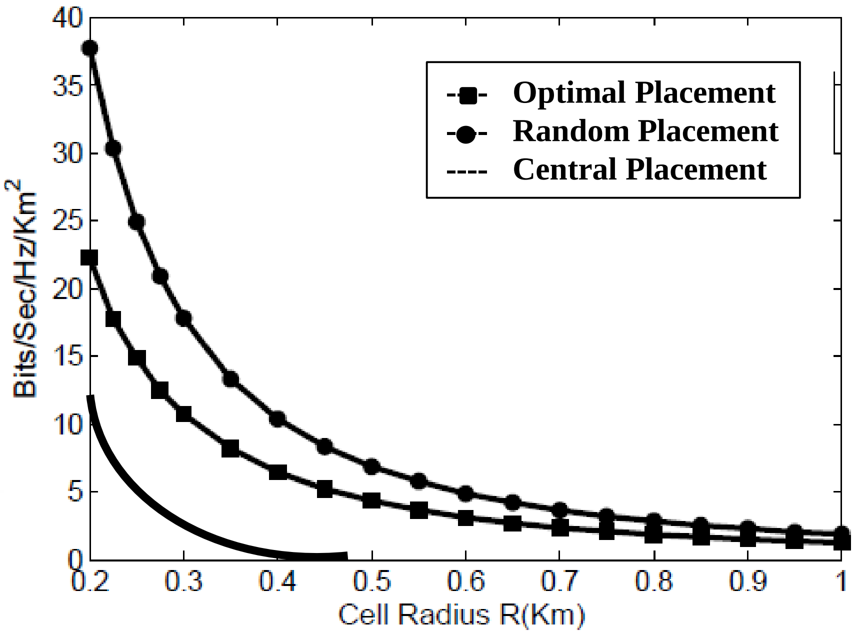
- Traditional cellular design "interference-limited"
  - MIMO/multiuser detection can remove interference
  - Cooperating BSs form a MIMO array: what is a cell?
  - Relays change cell shape and boundaries
  - Distributed antennas move BS towards cell boundary
  - Femtocells create a cell within a cell
  - Mobile cooperation via relaying, virtual MIMO, analog network coding.

Gains from Distributed Antennas

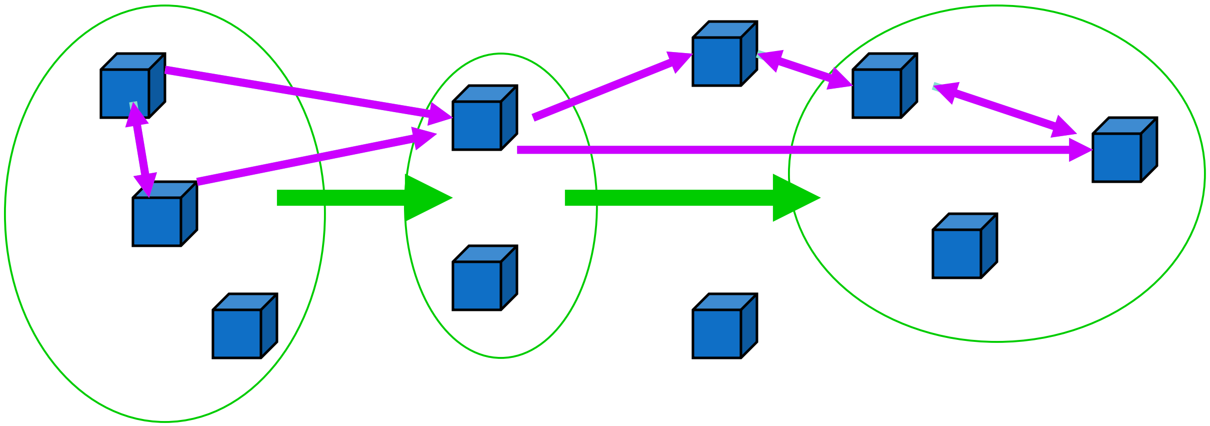
- 10x power efficiency gain with 3 distributed antennas
- 3-4x gain in area spectral efficiency
  - Small cells yield another 3-4x gain





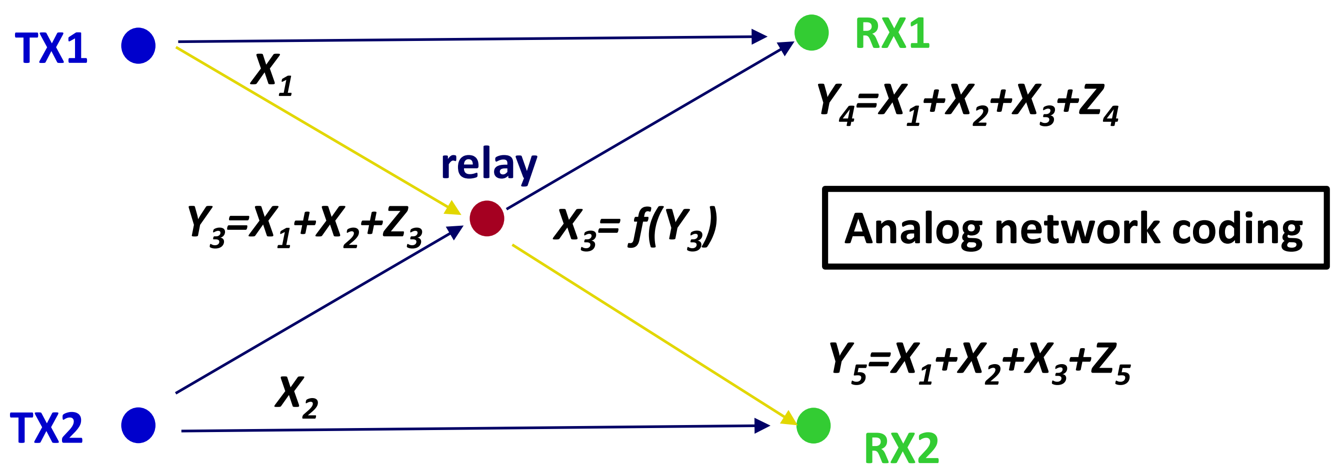


Cooperation in Ad-Hoc Networks



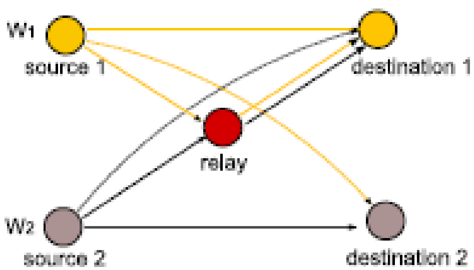
- Similar to mobile cooperation in cellular:
  - Virtual MIMO , generalized relaying, interference forwarding, and one-shot/iterative conferencing
- Many theoretical and practice issues:
  - Overhead, half-duplex, grouping, dynamics, synch, …

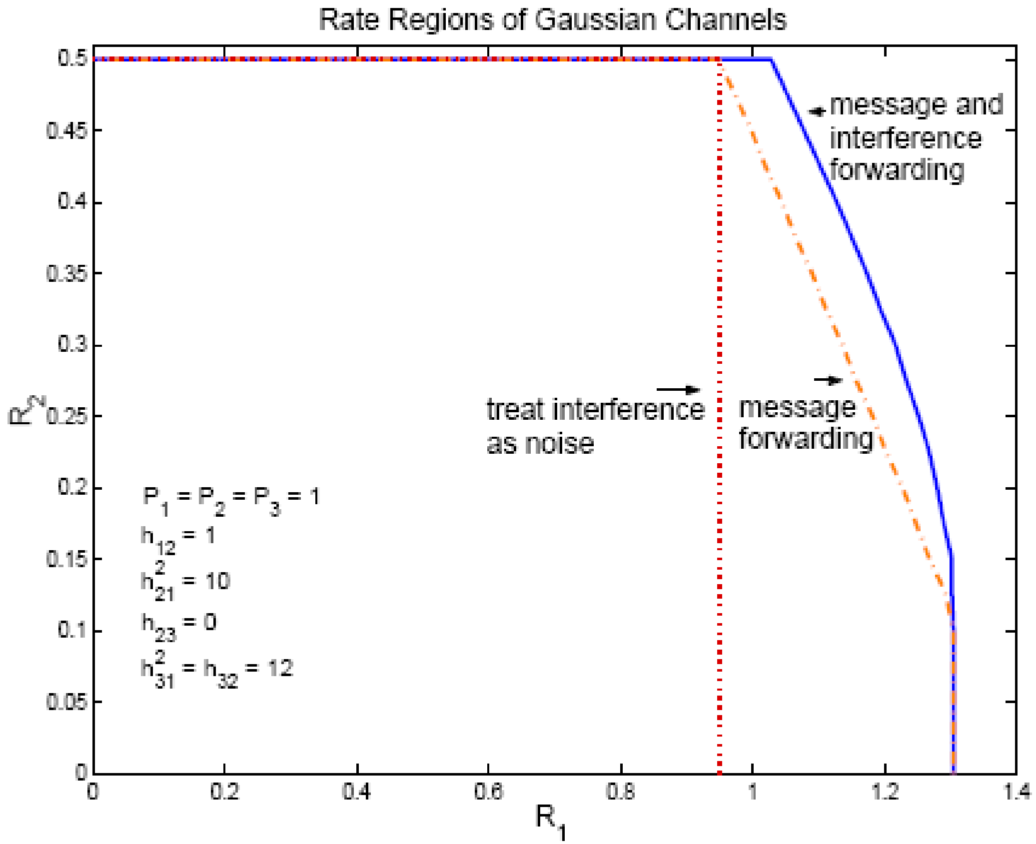
Generalized Relaying



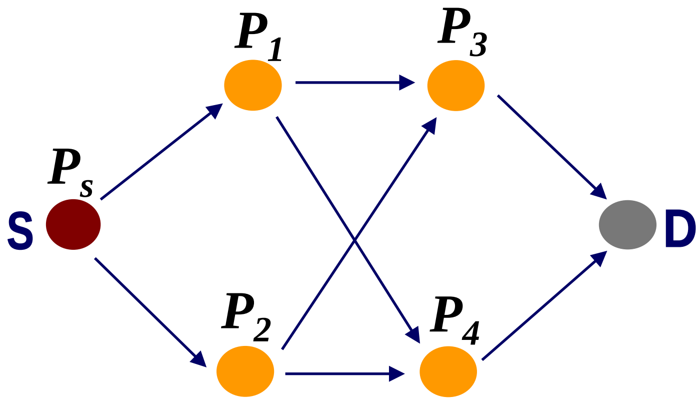
- Can forward message and/or interference
  - Relay can forward all or part of the messages
    - Much room for innovation
  - Relay can forward interference
    - To help subtract it out

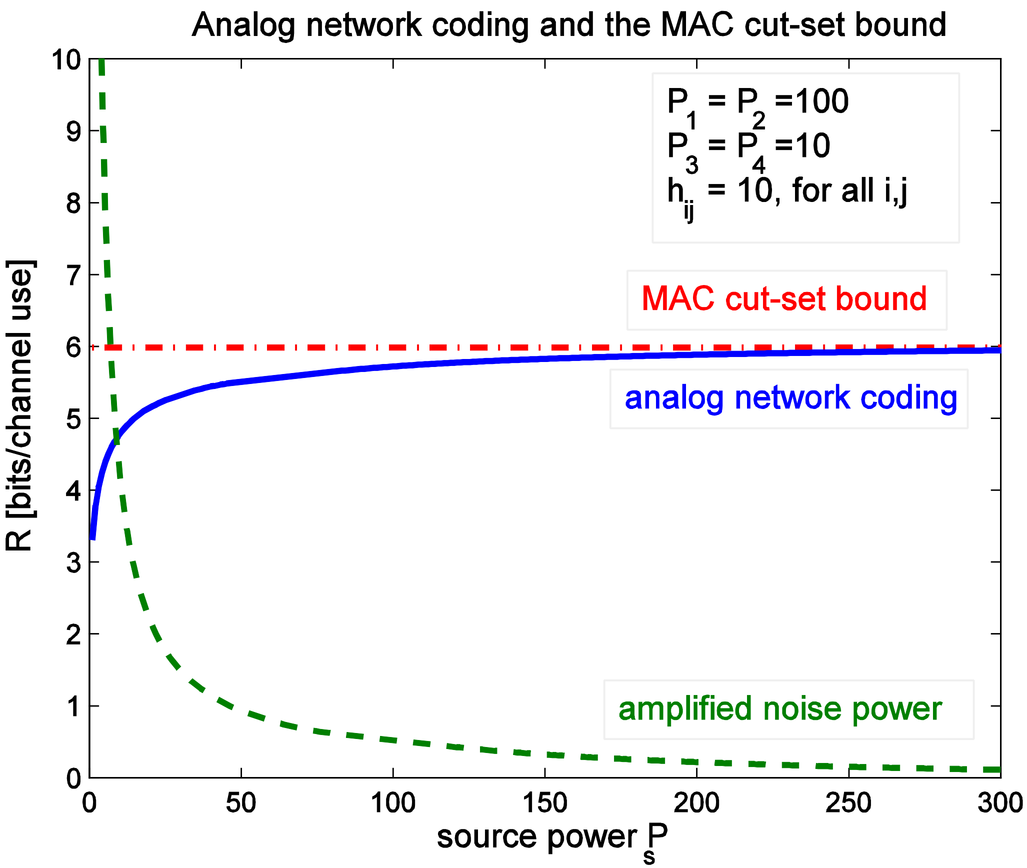
Beneficial to forward both interference and message





In fact, it can achieve capacity





- **For large powers P_s, P_1, P_2, analog network coding approaches capacity**

Intelligence beyond Cooperation: *Cognition*

- Cognitive radios can support new wireless users in existing crowded spectrum
  - <u>Without degrading performance of existing users</u>

- Utilize advanced communication and signal processing techniques
  - Coupled with novel spectrum allocation policies

- Technology could
  - Revolutionize the way spectrum is allocated worldwide
  - Provide sufficient bandwidth to support higher quality and higher data rate products and services

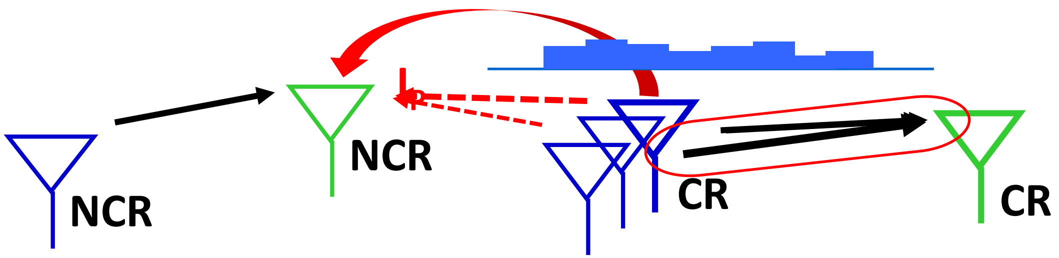
Cognitive Radio Paradigms

- Underlay
  - Cognitive radios constrained to cause minimal interference to noncognitive radios
- Interweave
  - Cognitive radios find and exploit spectral holes to avoid interfering with noncognitive radios
- Overlay
  - Cognitive radios overhear and enhance noncognitive radio transmissions

Knowledge and Complexity

Underlay Systems

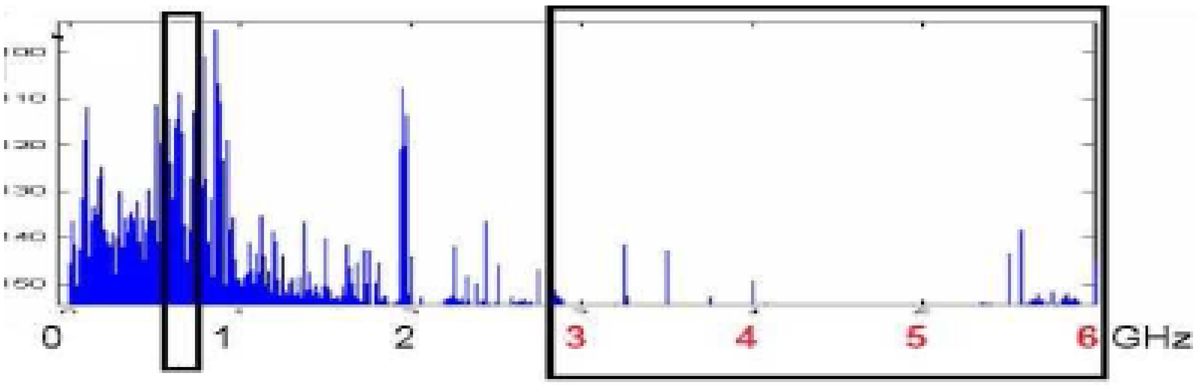
- Cognitive radios determine the interference their transmission causes to noncognitive nodes
  - Transmit if interference below a given threshold



- The interference constraint may be met
  - Via wideband signalling to maintain interference below the noise floor (spread spectrum or UWB)
  - Via multiple antennas and beamforming

Interweave Systems

- Measurements indicate that even crowded spectrum is not used across all time, space, and frequencies
  - Original motivation for "cognitive" radios (Mitola'00)

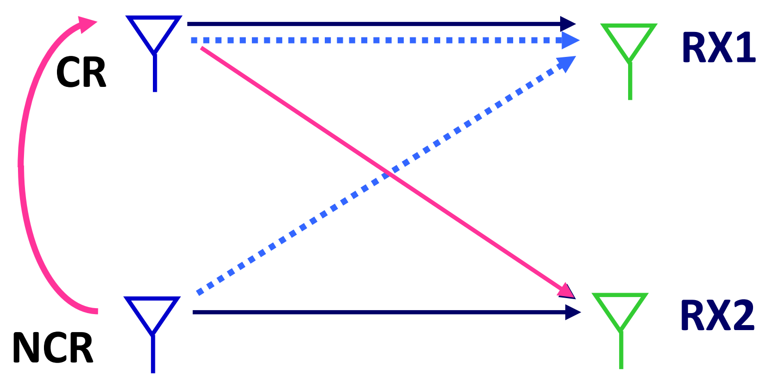


- These holes can be used for communication
  - Interweave CRs periodically monitor spectrum for holes
  - Hole location must be agreed upon between TX and RX
  - Hole is then used for opportunistic communication

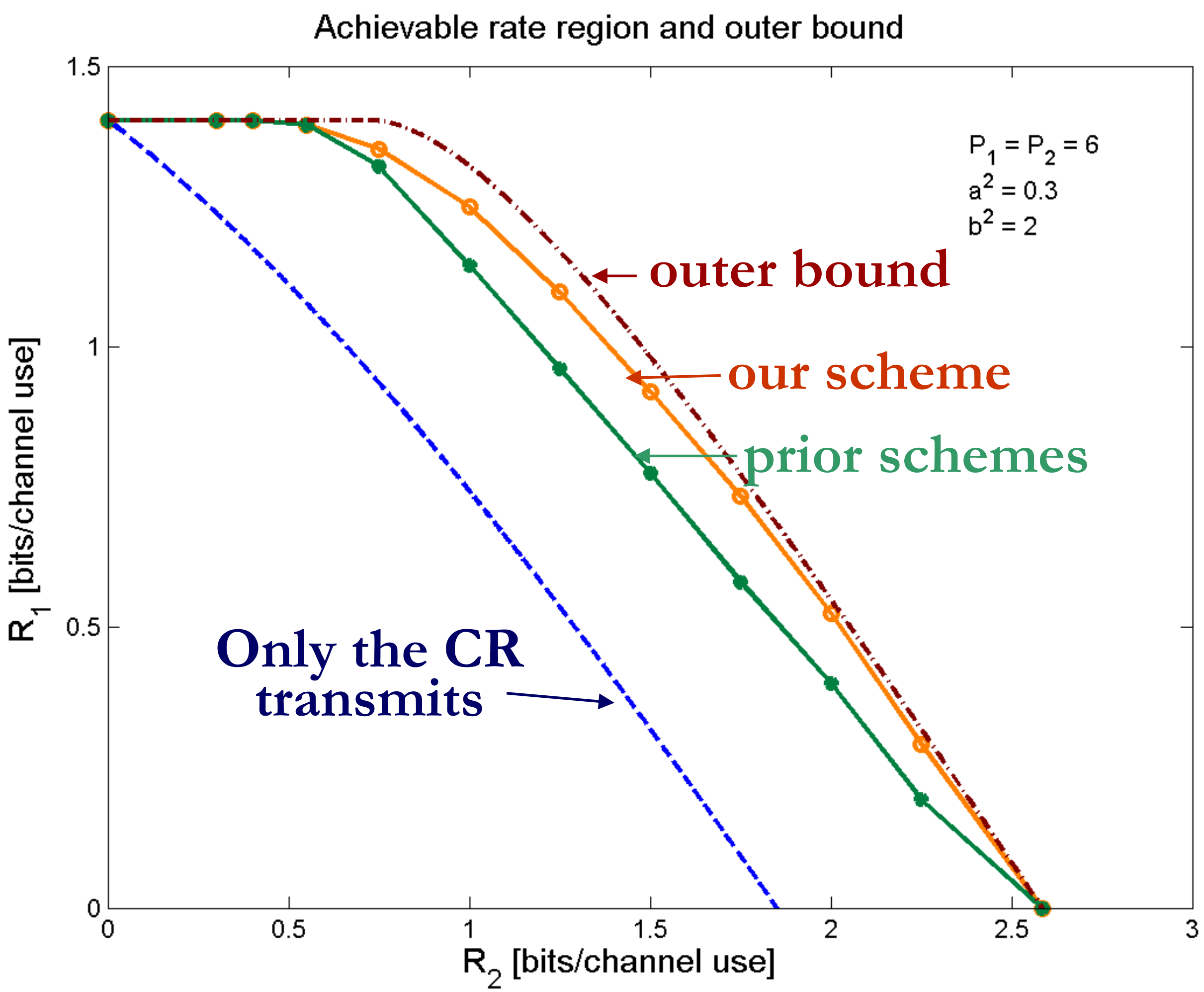
Compressed sensing reduces A/D and processing requirements

Overlay Cognitive Systems

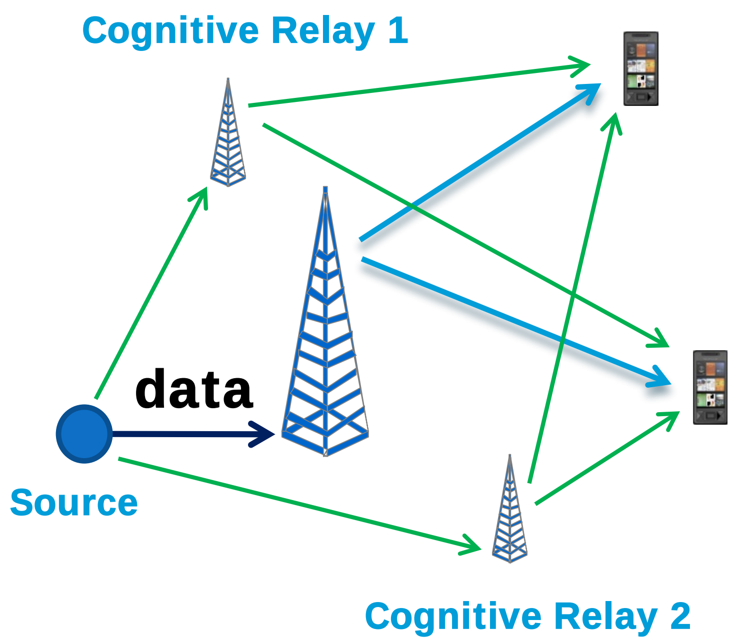
- Cognitive user has knowledge of other user's message and/or encoding strategy
  - Can help noncognitive transmission
  - Can presubtract noncognitive interference



Performance Gains from Cognitive Encoding



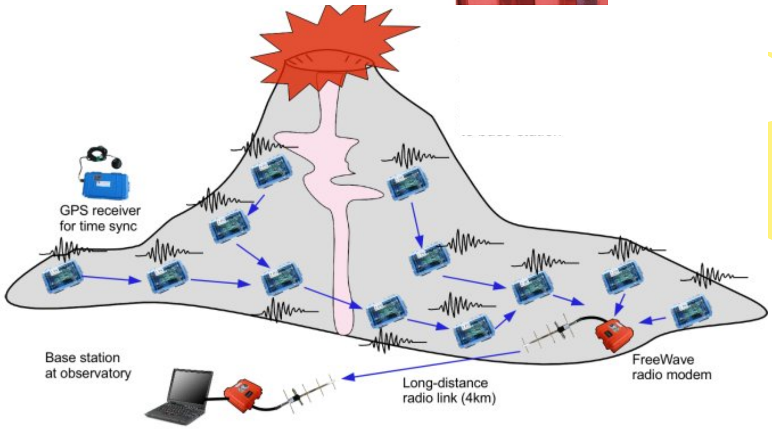
Cellular Systems with Cognitive Relays

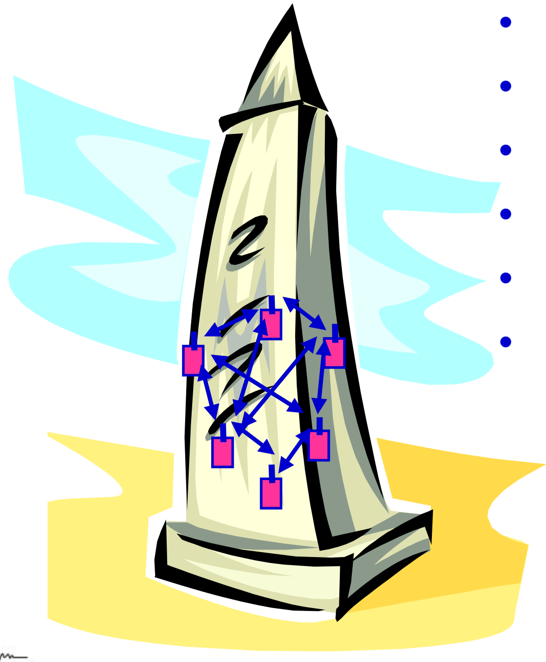


- Enhance robustness and capacity via cognitive relays
  - Cognitive relays overhear the source messages
  - Cognitive relays then cooperate with the transmitter in the transmission of the source messages
  - Can relay the message even if transmitter fails due to congestion, etc.

Can extend these ideas to MIMO systems

Wireless Sensor Networks





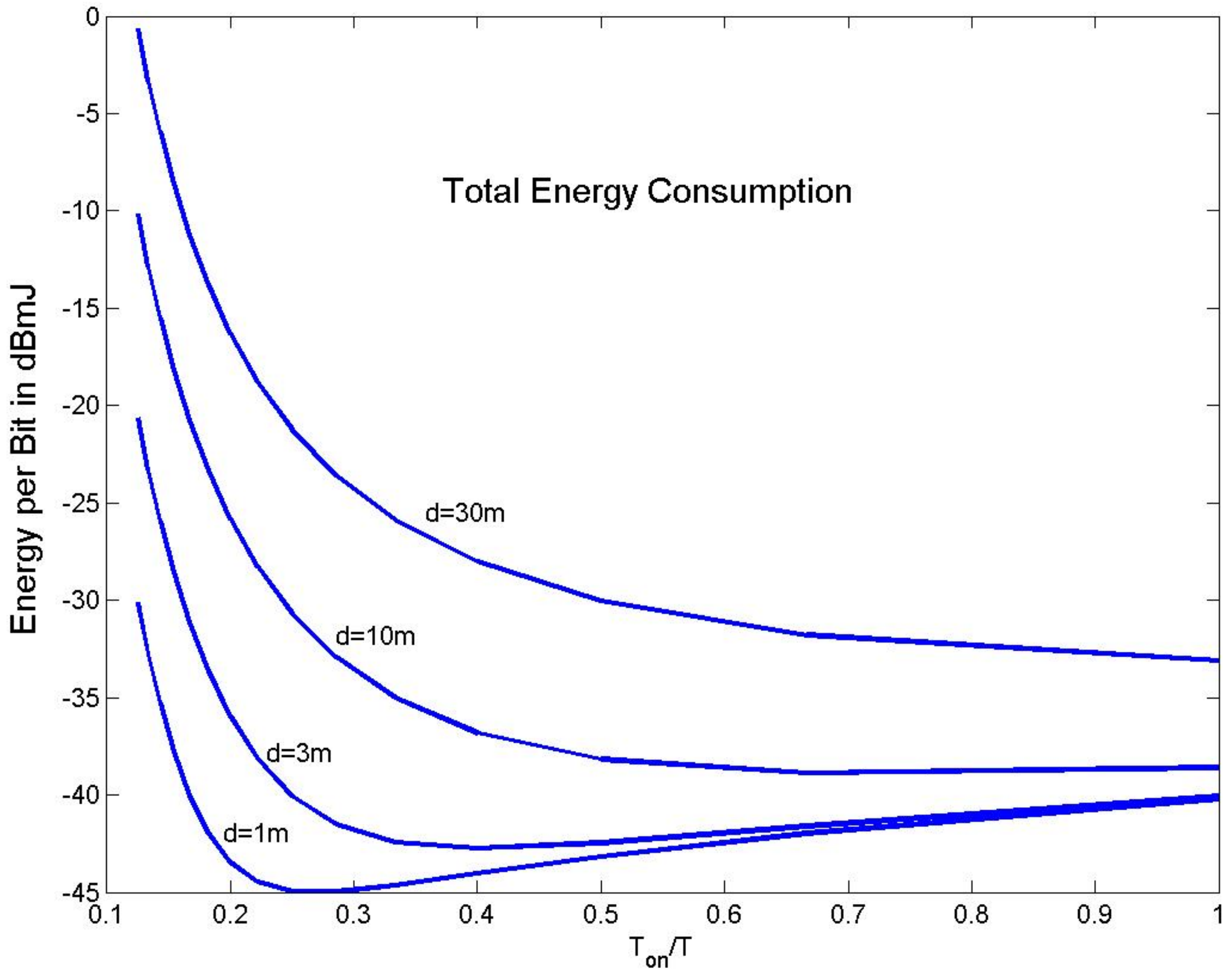
- Smart homes/buildings
- Smart grid
- Search and rescue
- Homeland security
- Event detection
- Battlefield surveillance

- Energy (transmit and processing) is the driving constraint
- Data flows to centralized location (joint compression)
- Low per-node rates but tens to thousands of nodes
- Intelligence is in the network rather than in the devices

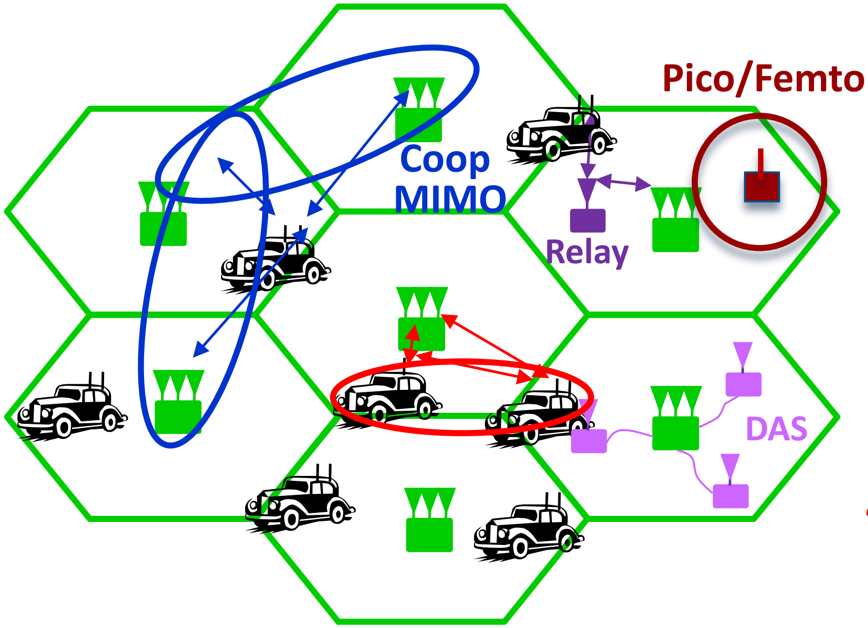
Cross-Layer Tradeoffs under Energy Constraints

- Hardware
  - All nodes have transmit, sleep, and transient modes
  - Each node can only send a <u>finite</u> number of bits
- Link
  - High-level modulation costs transmit energy but saves circuit energy (shorter transmission time)
  - Coding costs circuit energy but saves transmit energy
- Access
  - Power control impacts connectivity and interference
  - Adaptive modulation adds another degree of freedom
- Routing:
  - Circuit energy costs can preclude multihop routing

Total Energy (MQAM)



Green” Cellular Networks



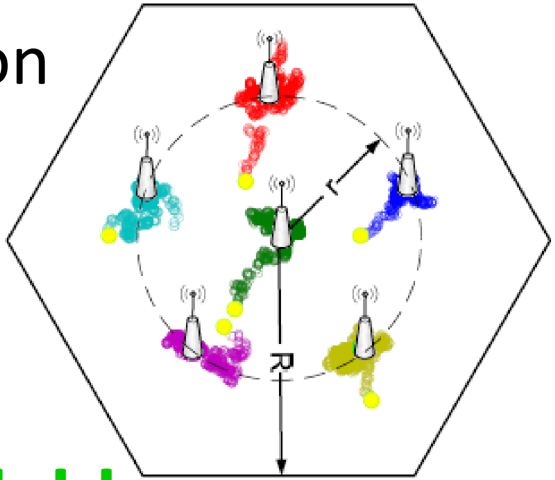
How should cellular systems be redesigned for minimum energy?

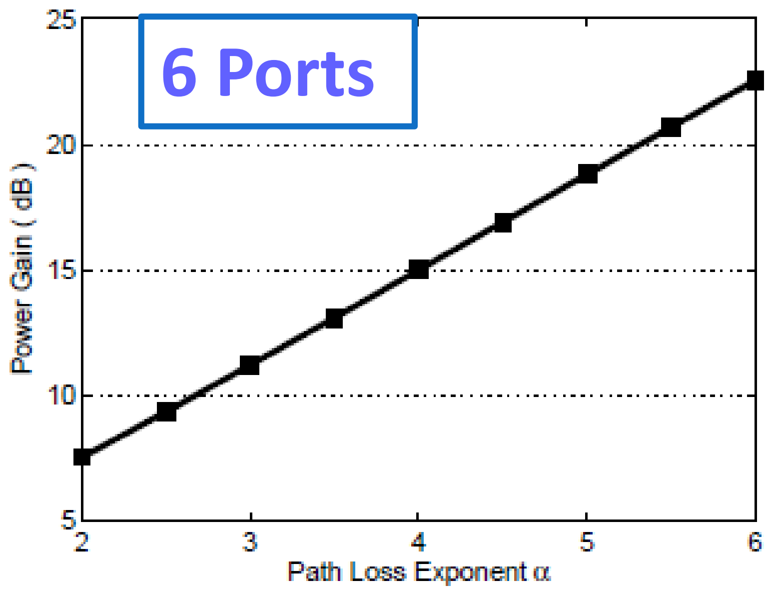
Research indicates that signicant savings is possible

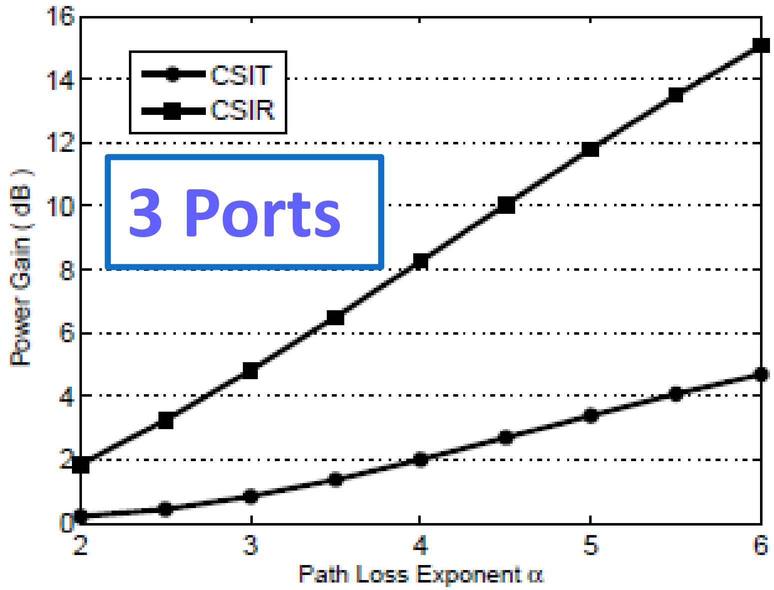
- Minimize energy at both the mobile *and* base station via
  - New Infrastructures: cell size, BS placement, DAS, Picos, relays
  - New Protocols: Cell Zooming, Coop MIMO, RRM, Scheduling, Sleeping, Relaying
  - Low-Power (Green) Radios: Radio Architectures, Modulation, coding, MIMO

Antenna Placement in DAS

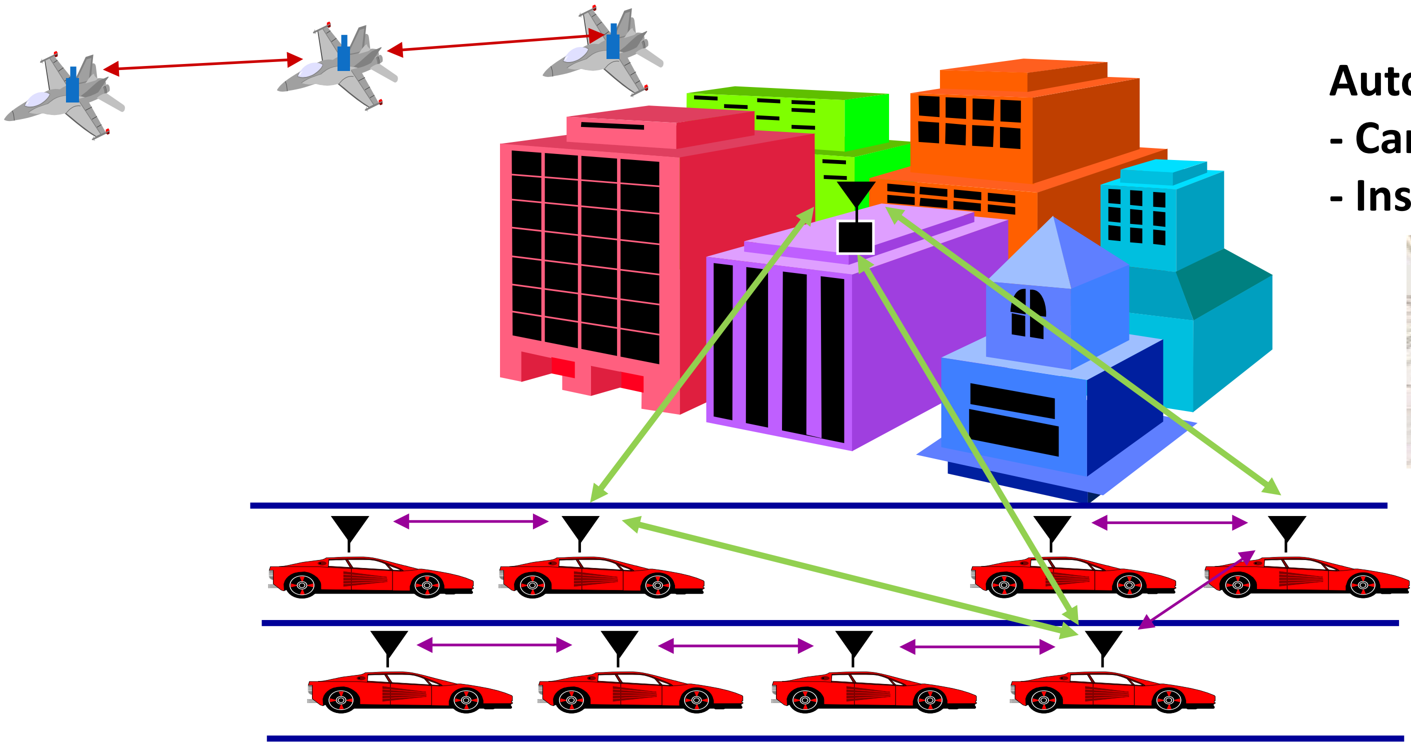
- Optimize distributed BS antenna location
- Primal/dual optimization framework
- Convex; standard solutions apply
- For 4+ ports, one moves to the center
- **Up to 23 dB power gain in downlink**
  - **Gain higher when CSIT not available**







Distributed Control over Wireless

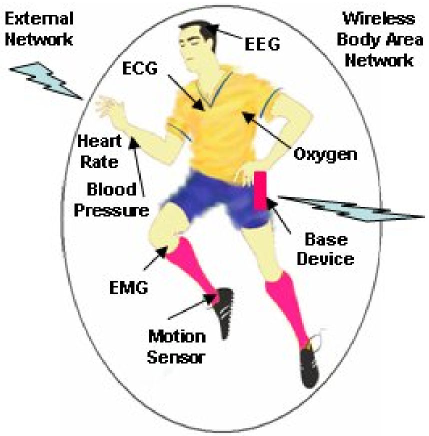


Automated Vehicles
- Cars/planes/UAVs
- Insect flyers

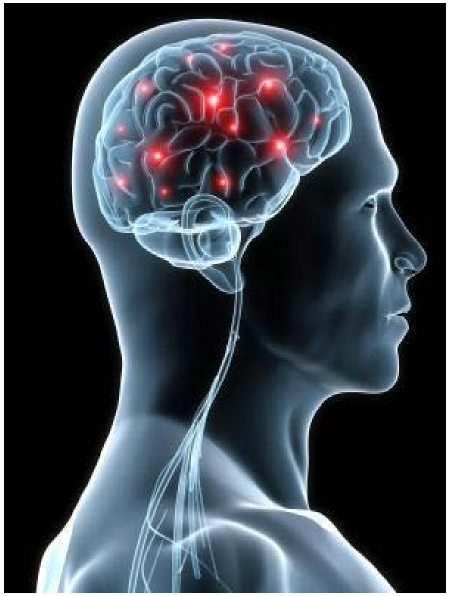
Interdisciplinary design approach

- Control requires fast, accurate, and reliable feedback.
- Wireless networks introduce delay and loss
- Need reliable networks and robust controllers
- Mostly open problems: *Many design challenges*

Wireless and Health, Biomedicine and Neuroscience



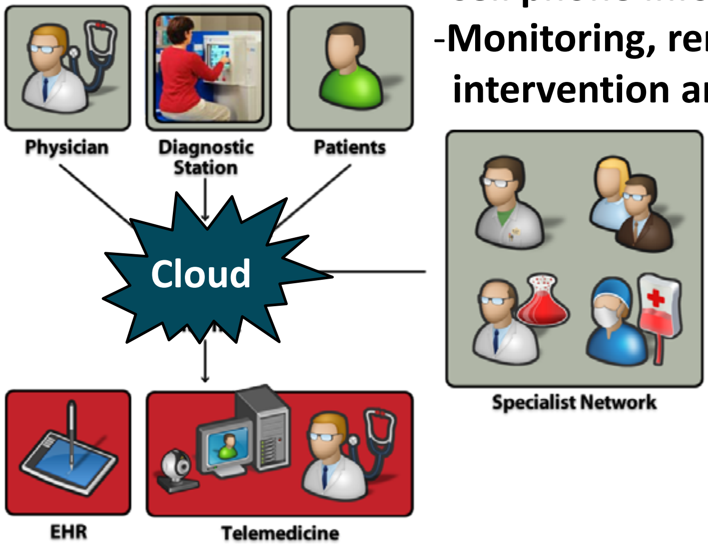
Body-Area Networks



Doctor-on-a-chip

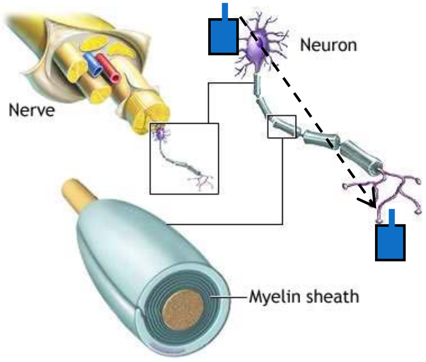
-Cell phone info repository

-Monitoring, remote intervention and services



The brain as a wireless network

- EKG signal reception/modeling
- Signal encoding and decoding
- Nerve network (re)configuration



Summary

- The next wave in wireless technology is upon us
- This technology will enable new applications that will change people's lives worldwide
- Design innovation will be needed to meet the requirements of these next-generation systems
- A systems view and interdisciplinary design approach holds the key to these innovations